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GALACTIC MAGNETIC FIELDS AND THE LARGE-SCALE ANISOTROPY AT MILAGRO

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ABSTRACT

The air-shower observatory Milagro has detected a large-scale anisotropy of unknown origin in the flux of TeV cosmic rays. We propose that this anisotropy is caused by galactic magnetic fields and, in particular, that it results from the combined effects of the regular and the turbulent (fluctuating) magnetic fields in our vicinity. Instead of a diffusion equation, we integrate Boltzmann's equation to show that the turbulence may define a *preferred* direction in the cosmic ray propagation that is orthogonal to the local regular magnetic field. The approximate dipole anisotropy that we obtain explains Milagro's data well.

Key words: cosmic rays – ISM: magnetic fields – solar neighborhood

1. INTRODUCTION

High-energy cosmic rays are of great interest in astrophysics, as they provide a complementary picture of the sky. When they are neutral particles (photons or neutrinos), they carry direct information from their source (Weekes, 2008; Voelk & Bernloehr 2009; Achterberg et al. 2006). During the past 30 years, gamma rays, in particular, have revealed a large number of astrophysical sources (quasars, pulsars, blazars) in our Galaxy and beyond. In contrast, when they are charged particles (protons, electrons, and atomic nuclei) cosmic rays lose directionality due to interactions with the μG magnetic fields that they face along their trajectory (Strong et al. 2007). In this case, however, they bring important information about the environment where they have propagated. For example, the simple observation that Boron is abundant in cosmic rays while rare in solar system nuclei is a very solid hint that cosmic rays have crossed around 10 g cm^{-2} of interstellar (baryonic) matter before they reach the Earth.

A very remarkable feature in the proton and nuclei fluxes is its isotropy. It is thought that cosmic rays of energy below 10^6 GeV are mainly produced in supernova explosions, which are most frequent in the galactic arms. We observe, however, that they reach us equally from all directions. This can only be explained if their trajectories are close to the random walk typical of a particle in a *gas*, and galactic magnetic fields seem the key ingredient in order to justify this picture.

Galactic magnetic fields have been extensively reviewed in the literature (Beck 2004, 2005; Wielebinski 2005; Han 2009; Battaner 2009). It is known that there is an average magnetic field of order

$$B_{\text{galactic}} \approx 3\ \mu\text{G} \tag{1}$$

at galactic scales. This component is the background to a second component of strength

$$B_{\text{random}} \approx 3\text{–}5\ \mu\text{G} \tag{2}$$

that is regular within cells of 10–100 pc but changes randomly from cell to cell. These magnetic fields have frozen-in field lines and are very affected by the compressions and expansions of the interstellar medium produced by the passage of spiral arm waves. A 10 TeV cosmic proton would move inside a 5 μG field with a gyroradius of

$$r_g = \frac{p}{eB} \approx 2 \times 10^{-3}\ \text{pc}\ , \tag{3}$$

which is much smaller than the typical region of coherence. Therefore, this proton *sees* the superposition of both components as a regular magnetic field:

$$\vec{B}_{\text{galactic}} + \vec{B}_{\text{random}} = \vec{B}_{\text{regular}} \equiv \vec{B}\ . \tag{4}$$

Note that the determination of the galactic field using *WMAP* data (Page et al. 2007; Jansson et al. 2009; Ruiz-Granados et al. 2009) gives $\vec{B}_{\text{galactic}}$. In contrast, estimates from Faraday rotations of pulsars would be sensitive to the same regular $\vec{B}$ that affects the cosmic proton. According to Han and collaborators (Han et al. 1999; Han 2009), the local $\vec{B}$ should be nearly contained in the galactic plane and clockwise as seen from the north galactic pole (i.e., following the direction of the disk rotation), although with a small vertical component or *tilt* angle.

At these small scales, the 10 TeV proton is *diffused* by scattering on random fluctuations in the magnetic field

$$\delta B \ll B\ . \tag{5}$$

The interaction is of resonant character, so that the particle is predominantly scattered by those irregularities of the magnetic field of wavenumber $k \approx 1/r_g$. Estimates from the standard theory of plasma turbulence (Casse et al. 2002) that δB falls as a power law for larger wavenumbers (Han 2009), so this component is smaller than the regular B.

In this Letter, we argue that the detailed observation of the TeV cosmic-ray flux obtained by Milagro (Abdo et al. 2008, 2009) also may provide valuable information about $\vec{B}$ and δB. In particular, the analysis of over 10^{11} air showers has produced a map of the sky showing a large-scale anisotropy (a north galactic deficit) of order 10^{-3}. This map, which is consistent with previous observations (Aglietta et al. 1996; Amenomori et al. 2006), remains basically unexplained. Abdo et al. have discussed several possible origins:

(i) The Compton–Getting (CG) effect (Compton & Getting 1935), a dipole anisotropy that arises due to the motion of the solar system around the galactic center and through the cosmic-ray background. The anisotropy observed in Milagro's map, however, cannot be fitted by the predicted CG dipole. In addition, the CG anisotropy should be energy independent, which does not agree with the data either.

(ii) The heliosphere magnetic field could produce anisotropies (Nagashima et al. 1998; Schlickeiser et al. 2007) that can

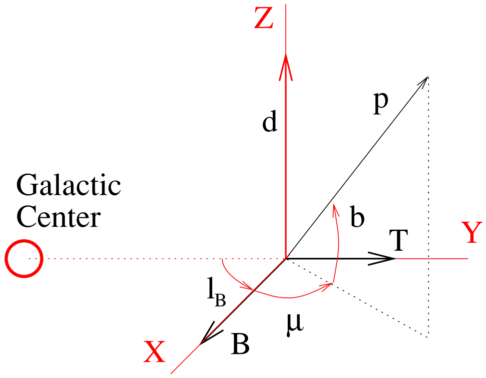

Figure 1. Angles b and μ, and orthogonal vectors $\vec{B}$, $\vec{T}$, and $\vec{d}$ for $l_B = 90°$.

also be ruled out. The Larmor radius r_g sets the size of the coherence cells, and for 10 TeV protons it is around 2×10^{-3} pc, significantly larger than the 5×10^{-4} pc (100 AU) of the heliosphere. Moreover, as pointed out in Abdo et al. (2009), the anisotropies persist at higher energies (i.e., for larger distance scales), supporting the hypothesis that if magnetic fields are involved they are extra-heliospheric.

Here we explore the effect of the local (regular and fluctuating) magnetic fields on the propagation of TeV cosmic rays reaching the Earth. Most analyses model cosmic-ray propagation with a diffusion equation (Ptuskin et al. 2006; Strong et al. 2007; Schlickeiser et al. 2007), assuming a certain spatial distribution of sources and a diffusion tensor often simplified to an isotropic scalar coefficient. This provides the flux over an extended region around the solar neighborhood. Here we intend a different approach. The diffusion equation derives from Boltzmann's equation, which contains *more* information. The solution of Boltzmann's equation in the vicinity of the Earth gives the statistical distribution function $f(\vec{r}, \vec{p}, t)$, a quantity related to the intensity or surface brightness used in astrophysics. f provides the number of cosmic rays per unit solid angle, time, and surface from any given direction, so it can be compared with Milagro's data pixel by pixel.

2. COSMIC-RAY DISTRIBUTION FUNCTION

We will treat TeV cosmic rays as a fluid that microscopically interacts only with the magnetic fields, and our objective is to obtain the distribution function $f(\vec{r}, \vec{p}, t)$ using Boltzmann's equation. We will take a basic *cell* of radius r_g and will assume that the non-turbulent component of the fluid is stationary and homogeneous. At these relatively small distance (and time) scales we also can neglect cosmic-ray sources, energy loss, or collisions with interstellar matter. In addition, we take the cosmic rays as protons (the dominant component in the flux) of $E = 6$ TeV (the average energy in Milagro's analysis). Finally, we will assume that the regular magnetic field $\vec{B}$ is on the galactic plane with a galactic longitude l_B, although we will show that Milagro's data favor a component orthogonal to this plane (as found in other observations, Han et al. 1999). In Figure 1, we have depicted $\vec{B}$ with $l_B = 90°$.

The frequency of the (b, μ) direction in the momentum of cosmic rays reaching the Earth is then proportional to[1]

$$f(\vec{u}) = f(b, \mu), \tag{6}$$

where $\vec{u} = \vec{p}/p$, b is the galactic latitude, and μ is the longitude relative to the direction of the magnetic field $\vec{B}$. Note that the galactic longitude of the direction defined by $\vec{u}$ is just $l = l_B + \mu$.

Boltzmann's equation expresses in differential form how particles move in the six-dimensional phase space (Battaner, 1996). In our case this is just

$$\vec{F} \cdot \nabla_u \, f(\vec{u}) = e\,(\vec{u} \times \vec{B}) \cdot \nabla_u \, f(\vec{u}) = 0\,. \tag{7}$$

Now, we separate the regular and the turbulent components both in the distribution function and in the magnetic field:

$$\begin{aligned} f &\to f + \delta f, \\ \vec{B} &\to \vec{B} + \delta\vec{B}. \end{aligned} \tag{8}$$

The components $\delta\vec{B}$ and δf vary randomly from one cell to another and have a vanishing average value,

$$[\delta\vec{B}] = [\delta f] = 0. \tag{9}$$

However, there may be correlations between both fluctuating quantities. In particular, we will assume a non-zero value of

$$\begin{aligned} [e\,(\vec{u} \times \delta\vec{B}) \cdot \nabla_u \, \delta f] &= e\,\vec{u} \cdot [\delta\vec{B} \times \nabla_u \, \delta f] \\ &= e\,\vec{u} \cdot \vec{T}. \end{aligned} \tag{10}$$

Boltzmann's equation for the regular component is then

$$(\vec{u} \times \vec{B}) \cdot \nabla_u \, f + \vec{u} \cdot \vec{T} = 0. \tag{11}$$

This equation can also be written as

$$\vec{u} \cdot (\vec{B} \times \nabla_u \, f) + \vec{u} \cdot \vec{T} = 0. \tag{12}$$

As $\vec{u}$ is any direction, this implies $\vec{B} \times \nabla_u \, f = \vec{T}$, i.e., the vector $\vec{T}$ must be orthogonal to $\vec{B}$. Taking $\vec{T}$ in the galactic plane,

$$\vec{u} \cdot \vec{T} = T \, \cos b \, \sin\mu, \tag{13}$$

and expressing

$$\nabla_u \, f = \frac{\partial f}{\partial b}\,\vec{u}_b + \frac{1}{\cos b}\,\frac{\partial f}{\partial \mu}\,\vec{u}_\mu \tag{14}$$

with

$$\begin{aligned} \vec{u}_b &= -\sin b \, \cos\mu \, \vec{u}_\phi - \sin b \, \sin\mu \, \vec{u}_r + \cos b \, \vec{u}_z; \\ \vec{u}_\mu &= -\sin\mu \, \vec{u}_\phi + \cos\mu \, \vec{u}_r, \end{aligned} \tag{15}$$

Equation (11) becomes

$$-\sin\mu \, \frac{\partial f}{\partial b} + \tan b \, \cos\mu \, \frac{\partial f}{\partial \mu} + \frac{T}{B} \, \cos b \, \sin\mu = 0\,. \tag{16}$$

This equation can be solved analytically:

$$f(b, \mu) = f_0 \left(1 + \frac{T}{f_0 B} \, \sin b \right) + \tilde{f}(\cos b \, \cos\mu)\,, \tag{17}$$

with f_0 being a constant that normalizes f to the number of particles per unit volume and the second term any arbitrary function of the variable $\cos b \, \cos\mu$. From the direction $\vec{u}$ we observe cosmic rays with $\vec{p} = -p\,\vec{u}$; it is straightforward to find the relation between the distribution function and the flux

[1] $(E/c)^2 f(\vec{u})$ gives the number of particles with momentum along $\vec{u}$ per unit energy, volume, and solid angle at $E \approx 6$ TeV.

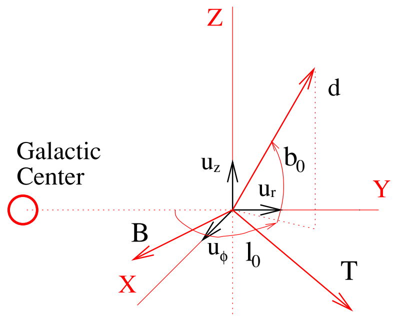

Figure 2. Trihedron defined by $\vec{B}$, $\vec{d}$, and $\vec{T}$, and the coordinate system. $\vec{B}$ is in the galactic plane, whereas $\vec{d}$ and $\vec{T}$ have latitudes b_0 and $90^\circ - b_0$, respectively.

$F(b, \mu)$ of particles observed at Milagro per unit area, time, solid angle, and energy:

$$F(b, \mu) = \frac{E^2}{c^2}\, f(-b, \mu + \pi)\ . \qquad (18)$$

This implies that

$$F(b, \mu) = F_0\,(1 - t\ \sin b) + \tilde{F}(\cos b\ \cos\mu)\ , \qquad (19)$$

where $t = T/(f_0 B)$ and $F_0 = (E/c)^2 f_0$. Finally, we will expand $\tilde{F}$ to second order:

$$\tilde{F}(\cos b\ \cos\mu) \approx F_1 \cos b\ \cos\mu + F_2\,(\cos b\ \cos\mu)^2\ . \qquad (20)$$

The solution in terms of the galactic longitude is obtained just by expressing $\mu = l - l_B$.

Several comments are here in order.

(i) If $F_1 = F_2 = 0$, then the solution is a dipole anisotropy, with the minimum/maximum in the north/south galactic poles. This dipole is then *modulated* by the constants $F_{1,2}$, that introduce an anisotropy proportional to $\cos b \cos\mu$ (i.e., the additional anisotropy coincides along the directions $\vec{u}$ with equal projection on $\vec{B}$).

(ii) The dipole anisotropy would vanish if there were no turbulence ($t = 0$): $\vec{B}$ implies an isotropy broken by the turbulence in the orthogonal plane. In contrast, the equation does not say anything about the direction along $\vec{B}$. For different boundary conditions one can find solutions with a forward–backward asymmetry (implying diffusion along $\vec{B}$) or symmetric solutions. In particular, F_1 creates an asymmetry between the ($b = 0$, $\mu = 0$) and ($b = 0$, $\mu = 180^\circ$) directions, whereas the F_2 contribution is symmetric.

(iii) The dominant magnetic field $\vec{B}$, the turbulence $\vec{T}$, and the dipole $\vec{d}$ are always orthogonal to each other. For $\vec{B} \approx B\vec{u}_\phi$ the symmetry of the galactic disk could favor a radial turbulence, $\vec{T} \approx T\vec{u}_r$, like the one that we have assumed above (see Figure 1).[2] However, one can change the latitude b_0 of the dipole while keeping $\vec{B}$ on the galactic plane just by taking the turbulence $\vec{T}$ out of the plane. In particular, the dipole will point toward the arbitrary direction b_0 (see Figure 2) if

$$\vec{u}\cdot\vec{T} = T\,(\sin b_0\ \cos b\ \sin\mu - \cos b_0\ \sin b)\ . \qquad (21)$$

[2] Buoyancy will mainly produce ascending turbulent cells; since Coriolis forces are negligible at these small timescales the compression of the (frozen-in) azimuthal field lines may result into a $\delta\vec{B}$ also azimuthal and a vertical $\nabla_u\,\delta f$, which imply a radial $\vec{T}$.

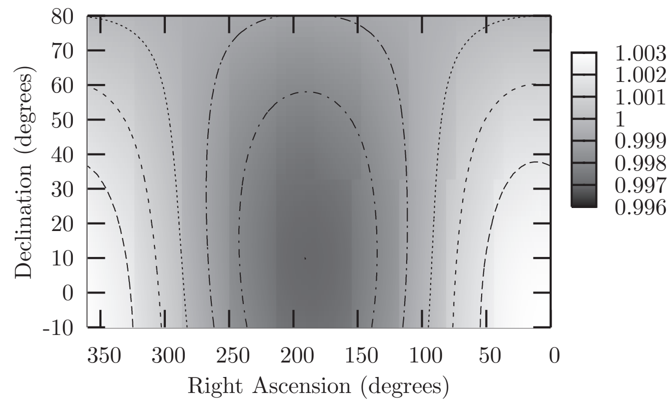

Figure 3. Fit of the Milagro anisotropy.

The dipole solution is in that case

$$F(b, \mu) = F_0\,[1 - t\,(\sin b_0\ \sin b + \cos b_0\ \cos b\ \sin\mu)] + F_1 \cos b\ \cos\mu + F_2\,(\cos b\ \cos\mu)^2\ . \qquad (22)$$

The galactic latitude l_0 of the dipole is then fixed by the orientation of $\vec{B}$ in the galactic plane,

$$l_0 = l_B + 90^\circ. \qquad (23)$$

The direction of the dipole in the basis pictured in Figure 2 is

$$\vec{u}_d = \cos b_0\ \sin l_0\ \vec{u}_\phi - \cos b_0\ \cos l_0\ \vec{u}_r + \sin b_0\ \vec{u}_z. \qquad (24)$$

3. MILAGRO DATA

Milagro data (Abdo et al. 2009) indicate a clear dipole anisotropy, with a deficit in the north galactic hemisphere that peaks at $\delta_0 \approx 10^\circ$ and $AR_0 \approx 190^\circ$ (i.e., $b_0 \approx 72^\circ$ and $l_0 \approx 293^\circ$). In Figure 3, we plot our fit of the data (restricted to a region in the sky), which is obtained for $t = 0.003$ with $F_1/F_0 = 0$, $F_2/F_0 = 0.0003$ and a magnetic field $\vec{B}$ along $l_B = 203^\circ$. Our simple fit, an approximate dipole along the direction of $\nabla_u f$ (from b_0, l_0 to $-b_0$, $l_0 - \pi$) provides a good description of Milagro's anisotropy.

The fit implies that cosmic rays move near the Earth with a mean velocity

$$\vec{v}_0/c = -\frac{1}{N}\int d\Omega\ F(\vec{u})\,\vec{u} = -0.00059\,\vec{u}_\phi - 0.00028\,\vec{u}_r + 0.00157\,\vec{u}_z, \qquad (25)$$

where $N = \int d\Omega\ F(\vec{u})$ and the basis is pictured in Figure 2. Equation (25) expresses the diffusion velocity of the fluid (the transport flux $\vec{J}$ is proportional to $N\vec{v}_0$), and we find that it goes exactly in the direction of the dipole (the term F_1 would change its direction but we have set it to zero).

It is important to note that the regular magnetic field $\vec{B}$ does *not* need to be on the galactic plane (our choice above), it can rotate around the dipole axis and still give the same dipole solution as far as the turbulence $\vec{T}$ is rotated as well. Doing that the only changes would appear in the boundary conditions (F_1 and F_2), but the pure dipole would provide the simplest solution in any case. The dipole seems to point toward

$$\vec{u}_d = -0.35\,\vec{u}_\phi - 0.16\,\vec{u}_r + 0.92\,\vec{u}_z. \qquad (26)$$

Therefore, we can check if this dipole observed at Milagro and the local regular magnetic field $\vec{B}$ (also an observational output) are perpendicular. We will consider the values of $\vec{u}_B$ given by Han (Han et al. 1999; Han 2009). It is found that $\vec{B}$ is basically azimuthal clockwise (a *pitch* angle of either 0° or 180° depending on the definition, which changes for different authors). However, the observations also indicate the presence of a non-null *tilt* angle of 6° (a vertical component of order 0.3 μG) taking the magnetic field out of the plane. We obtain an unitary vector

$$\vec{u}_B = 0.99\,\vec{u}_\phi + 0.00\,\vec{u}_r + 0.10\,\vec{u}_z\ , \tag{27}$$

which implies a remarkable

$$\vec{u}_d \cdot \vec{u}_B = -0.18. \tag{28}$$

We think that the approximate orthogonality of these two observational vectors (we obtain an angle of 100°) provides support to the model presented here.

Note that our framework could also accommodate other anisotropies in the flux, added to the dipole one, as far as they have the same value in all the points with equal projection ($\cos b \cos \mu$) on $\vec{B}$. To explain a *point-like* anisotropy like the one named as *region A* in Abdo et al. (2008), the anisotropy itself should be along the direction of the dominant magnetic field $\vec{B}$ (orthogonal to $\vec{d}$). *Region A*, however, is at ($b_A \approx$-30°, $l_A \approx 215°$), forming an angle of 58° with the dipole.

4. SUMMARY AND DISCUSSION

Although charged cosmic rays do not reveal their source, the study of their flux from different directions is of interest in astrophysics because it brings valuable information about the interstellar medium. In particular, the *per mille* deficit observed by Milagro could be caused by the local (at distances of order r_g) magnetic fields.

Using Boltzmann's equation we have shown that the interplay between the regular and the turbulent components in these magnetic fields always produces a dipole anisotropy in the cosmic-ray flux. We find that (i) the direction of this anisotropy is orthogonal to the regular $\vec{B}$ and (ii) its intensity is proportional to the fluctuations $\delta B/B$ at the wavenumber $k = 1/r_g$. These two simple results have already non-trivial consequences. In particular, (i) implies that a north–south galactic anisotropy would only be consistent with a dominant $\vec{B}$ laying in the galactic plane, whereas (ii) explains that the anisotropy is *larger* for more energetic cosmic rays: their gyroradius r_g is larger, the resonant wavenumber k smaller, so the expected value of $\delta B/B$ will be larger.

We have argued that Milagro's data can be interpreted as a dipole anisotropy pointing to a well-defined direction in the north galactic hemisphere, namely ($b_0 \approx 72°$, $l_0 \approx 293°$). Our model provides a remarkable fit of the data, so we conclude that it explains satisfactorily the large-scale anisotropy found by Milagro. The model implies that the dominant magnetic field near our position *must* be in the plane orthogonal to the dipole ($\vec{B}$, the turbulence correlation $\vec{T}$ and $\vec{d}$ define a trihedron). This plane forms an angle $\theta = 23°$ with the galactic disk.

The data obtained by Milagro (energy, direction, and nature of over 10^{11} primaries) show that the 10^{-3} deficit in the cosmic-ray flux from the north galactic hemisphere already seen in previous experiments (Aglietta et al. 1996; Amenomori et al. 2006) is actually very close to a dipole anisotropy. We think that the analysis of the flux after subtracting this dipole anisotropy could reveal further correlations.

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